

Discovery of microsecond time lags in kilohertz QPO

B. A. Vaughan

Space Radiation Laboratory, California Institute of Technology, MC 220-47, Pasadena CA 91125;
brian@srl.caltech.edu

M. van der Klis, M. Méndez¹, J. van Paradijs² and R. A. D. Wijnands

Astronomical Institute “Anton Pannekoek”, University of Amsterdam,
and Center for High Energy Astrophysics, Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands;
michiel@astro.uva.nl, mariano@astro.uva.nl, jvp@astro.uva.nl, rudy@astro.uva.nl

W.H.G. Lewin

Massachusetts Institute of Technology, Cambridge, MA 02139; lewin@space.mit.edu

F.K. Lamb and D. Psaltis

Departments of Physics and Astronomy, University of Illinois at Urbana-Champaign, Urbana, IL 61801;
f-lamb@uiuc.edu, demetris@astro.uiuc.edu

E. Kuulkers

Astrophysics, University of Oxford, Nuclear and Astrophysics Laboratory, Keble Road, Oxford OX1 3RH,
United Kingdom; e.kuulkers1@physics.oxford.ac.uk

T. Oosterbroek

Astrophysics Division, Space Science Department of ESA, ESTEC, P.O. Box 299, 2200 AG Noordwijk,
The Netherlands; toosterb@ests2.estec.esa.nl

ABSTRACT

Using the Rossi X-ray Timing Explorer we have measured $\sim 27\mu\text{s}$ time delays in 830 Hz quasi-periodic oscillations (QPO) between 4–6 keV and 11–17 keV in 4U 1608–52, with high-energy photons lagging low energy photons, and found upper limits to the time delays of $45\mu\text{s}$ between 2–6.5 keV and 6.5–67 keV in ~ 730 Hz QPO in 4U 0614+091 and $30\mu\text{s}$ between 8.7–12.4 keV and 12.4–67 keV in ~ 870 Hz QPO in 4U 1636–53. We also find that the cross coherence function between QPO at different energies is > 0.85 with 95% confidence in 4U 1608–52 and 4U 1636–53. If Compton upscattering of low-energy X-rays in a region with an optical depth of a few is responsible for the delays, then the Compton upscattering region is between a few kilometers and a few tens of kilometers in size.

Subject headings: accretion, accretion disks — stars: neutron — X-rays: stars — stars: individual (4U 1608–52, 4U 0614+614, 4U 1636–53)

¹Also Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, 1900 La Plata, Argentina

²Also Department of Physics, University of Alabama at Huntsville, Huntsville, AL 35899

1. Introduction

Quasi-periodic oscillations (QPO) with frequencies $\nu_{\text{QPO}} \sim 350 - 1170$ Hz have recently been observed in power spectra of countrate modulations in ~ 10 X-ray binaries. These QPO have fractional root-mean square (rms) amplitudes of 1–20%, and quality factors $Q \equiv \nu_{\text{QPO}}/\Delta\nu_{\text{QPO}} = 10 - 200$, where $\Delta\nu_{\text{QPO}}$ is the full width at half maximum of the QPO peak in the power spectrum. In six sources a pair of QPO peaks have been observed simultaneously (4U 0614+091, 4U 1728–34, Sco X-1, GX 5–1, 4U 1820–30, and 4U 1636–53), with frequencies separated by 200–400 Hz. In 4U 0614+091 and 4U 1728–34 the frequency separation remains constant during excursions in QPO frequency by ~ 200 Hz. QPO frequency is strongly correlated with count rate in 4U 1820–30, 4U 0614+091, and 4U 1728–34, and with \dot{M} as inferred from the Z-track in GX 5–1 and Sco X-1 (van der Klis et al. 1996). A 363 Hz oscillation seen during X-ray bursts in 4U 1728–34 (Strohmayer et al. 1996) has a frequency consistent with the difference between the pair of QPO peaks.

The frequencies of these QPO may correspond to the Keplerian frequency, ν_{Kep} , at the inner edge of the Keplerian flow, which may be terminated by radiation forces, general relativistic corrections to Newtonian gravity, or perhaps the magnetic field of the neutron star and to the difference, or beat, frequency between ν_{Kep} and the spin frequency of the neutron star (Alpar & Shaham 1985; Lamb et al. 1985; Miller, Lamb, & Psaltis 1997). The oscillations seen in 4U 1728–34 during some bursts, which have a frequency equal to the difference between the frequencies of the two higher-frequency QPO, suggests this interpretation. The changing difference between the frequencies of the high-frequency QPO seen in Sco X-1 (van der Klis et al. 1996) would then require the spin frequency to beat with a varying Keplerian frequency that is slightly different from the frequency of the higher-frequency QPO in this source.

In the Z sources GX 5–1 and Cyg X-2, countrate modulations at energies above ~ 5 keV lag those below ~ 5 keV by 1–10 ms in 15–55 Hz horizontal-branch QPO (van der Klis et al. 1987; Vaughan et al. 1994), with the delay increasing with photon energy, and by 70 ms in 6 Hz normal-branch QPO (Mitsuda & Dotani 1989; Vaughan et al. 1997; Dieters et al. 1997). In both cases, the cross coherence between oscillations at different energies is ~ 1 , meaning that they can be related to one another by a constant linear transformation. See Vaughan & Nowak 1997 for an explanation of the cross coherence function, also called the coherence function, or simply coherence. No lags have so far been detected in normal-branch QPO in Sco X-1 (Dieters et al. 1997). In the case of horizontal-branch oscillations, Compton upscattering of low-energy photons has been suggested as one possible explanation for the lags (Wijers, van Paradijs & Lewin 1987; Stollman et al. 1987; Bussard et al. 1988), although differences in the lag at the QPO fundamental frequency and its harmonic in GX 5–1 challenge this interpretation (Vaughan et al. 1994). It is also possible to interpret the lags in the context of shot noise models by postulating that individual shots “harden”, i.e., become hotter, as they progress. Hardening shots can be used to produce any time delay, but Vaughan & Nowak (1997) point out that for blackbody emission, hardening shots only result in unity cross coherence if the photons are emitted in the Rayleigh-Jeans part of the energy spectrum, in which case they lead to no delay. We report in this paper the discovery of $\sim 27 \mu\text{s}$ hard lags in kilohertz QPO and show that they are consistent with Compton upscattering in a region between a few kilometers and few tens of kilometers in size, i.e., comparable to the size of a neutron star.

Table 1: Observations and QPO Properties

System	Observation Date	Duration (s) ^a	Rate (s ⁻¹) ^b	ν_{QPO} (Hz)	RMS ^c	Range (Hz) ^d
4U 1608–52	3 March 1996	3694	3100	830	.07	820–840
4U 0614+091	16 March 1996	4918	560	730	.13	680–780
4U 1636–53	29 May 1996	2360	1700	870 ^e	.07	862–877

^aLength of data set used for analysis. Determined principally by the stability of the QPO frequency

^bAverage count rate of data used in the analysis

^cFractional RMS amplitude of the QPO. Increases with energy in all sources

^dRange of frequencies used for analysis. Dictated by the QPO width and stability of the QPO centroid frequency

^eAverage ν_{QPO} for the first 2360 s of the observation

2. Observations

We have investigated time delays in the QPO between different energy channels in 4U 1608–52, 4U 0614+091, and 4U 1636–53. These sources were chosen because each showed QPO with high fractional rms amplitude, a moderate to high count rate, a narrow peak, and a stable frequency during at least one extended interval. We also of course required spectrally-resolved data of sufficient time resolution.

All observations were performed using the Proportional Counter Array on the Rossi X-ray Timing Explorer (Bradt, Rothschild & Swank 1993). Observation times and durations, and count rates are given in Table 1, along with QPO properties (all of which were measured by previous investigators). Details of the QPO in these sources can be found in Berger et al. 1996 (4U 1608–52), Méndez et al. 1997 (4U 0614+091), and Wijnands et al. 1997 (4U 1636–53). A single QPO peak was present in each observation. We were unable to investigate time lags in observations containing two QPO peaks because data with sufficient signal strength were unavailable (see section 3). We calculated the cross-spectra in the way described in Vaughan et al. (1994).

Instrumental deadtime can cause a bias in measurements of time delays by introducing an anti-correlation between pairs of energy channels that manifests itself as a 180° phase difference in the cross spectrum between pairs of energy channels at all frequencies. Because the count rates for each of the sources investigated here were small compared with the inverse of the instrumental deadtime, the fractional deadtime was typically <1% and deadtime had a completely negligible effect on cross spectra measured at the QPO frequency.

3. Results

Measurement of time delays and the cross coherence function in the presence of a counting-noise background is discussed in detail in Vaughan et al. (1994) and Vaughan & Nowak (1997). The crucial quantity for determining whether a meaningful estimate of the time delay between two light curves is possible is the signal to noise ratio, S/N , given by $S/N = f_1 f_2 r_1^{1/2} r_2^{1/2} T^{1/2} \Delta\nu^{-1/2}$, where f_1 and f_2 are the fractional rms amplitude of the QPO in the 2 light curves, r_1 and r_2 are the count rates, T is the

duration of the measurement, and $\Delta\nu$ is the width of the frequency interval used for the measurement. This formula assumes the background count rate is much smaller than the source count rate and that the cross coherence between the light curves is unity. The smallest time difference that can be measured is $\delta t_{\min} = n_{\sigma}(2\pi\nu)^{-1}[\arctan(S/N)]^{-1} \approx n_{\sigma}(2\pi\nu)^{-1}(S/N)^{-1}$, where n_{σ} is the detection significance, in standard deviations.

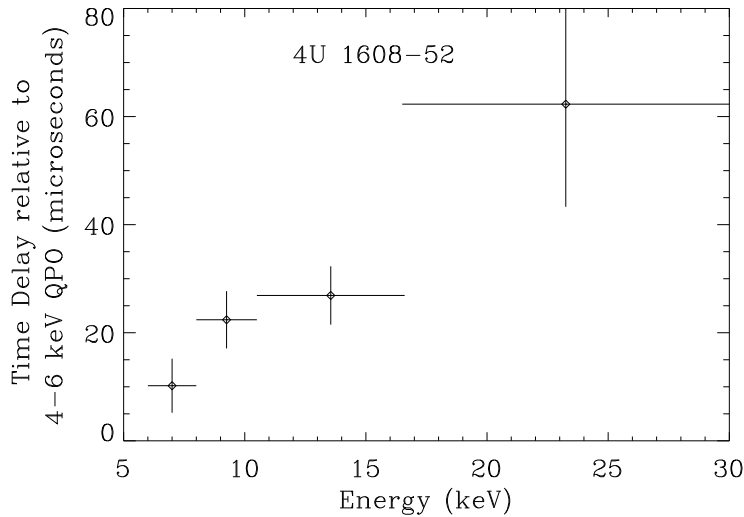


Fig. 1.— Time delays in 830 Hz QPO in 4U 1608–52 relative to 4–6 keV fluctuations, measured in the frequency range 820–840 Hz on 1996 March 3.

The observation from Table 1 best suited for measuring time delays is the 3 March 1996 observation of 4U 1608–52, for which $S/N \sim 40$ between energy channels of width ~ 2 keV at energies below ~ 12 keV. We divided the data containing strong ~ 830 Hz QPO into 5 energy channels covering the ranges 4–6 keV, 6–8.2 keV, 8.2–10.6 keV, 10.6–16.6 keV, and 16.6–30 keV, and measured the time delay and cross coherence function between all pairs of channels. The time delays are plotted in Figure 1 relative to the 4–6 keV channel. The sign convention is such that a positive time delay indicates that the higher energy channel lags behind the lower energy channel. The 8.2–10.6, 10.6–16.6, and 16.6–30 keV channels all lag the 4–6 keV channel with $> 3\sigma$ significance. The most significant lag (5σ) is between the 4–6 keV and 10.6–16.6 keV channel: $27 \pm 5 \mu\text{s}$. The cross coherence function between the channels is consistent with unity, and is > 0.9 with 95% confidence for all channels.

We are also able to significantly constrain the time delay in the single QPO peak at ~ 730 Hz observed 16 March 1996 in 4U 0614+091, and in the single QPO peak at ~ 870 Hz observed 29 May 1996 in 4U 1636–53, as well as the cross coherence in 4U 1636–53. In both cases, to optimize S/N , we divided the data into 2 energy channels. In 4U 06214+091 we find that the oscillations at 6.5–67 keV lag those at 2–6.5 keV by $26 \pm 23 \mu\text{s}$ and in 4U 1636–53 we find that the oscillations at 12.4–67 keV lag those at 8.7–12.4 keV by $-2.7 \pm 14 \mu\text{s}$. For these two systems we thus have 95% confidence upper limits on the time delay, δt , of $45 \mu\text{s}$ (4U 0614+091) and $30 \mu\text{s}$ (4U 1636–53). The 95% confidence lower limit to the cross coherence is 0.85 in 4U 1636–53. The cross coherence function of the QPO in 4U 0614–091 could not be meaningfully constrained since cross coherence is a 4th-order statistic with a large variance at small S/N . We attempted to investigate time lags in observations containing two simultaneous kilohertz QPO peaks. Our best candidate was a 28 February 1996 observation of 4U 1636–53 with QPO at 900 Hz and 1176 Hz

(Wijnands et al. 1997). We were unable to measure the time delay in either of the two QPO peaks due to low S/N .

The small lags we see cannot be due to large ($\delta t \gg 1/\nu$) and variable time differences that average out to zero. If the lags were large and variable, we would find phase differences $\delta\phi = 2\pi\nu\delta t$ uniformly and randomly distributed on $[-\pi, \pi]$, large error bars $\Delta(\delta\phi) \sim \pi$, and small cross coherence.

4. Discussion

We have measured time delays between the kilohertz QPO at different photon energies in 4U 1608–52, 4U 0614+091, and 4U 1636–53. In the first source we found a significant hard lag whereas in the latter two sources we found that any time delays are $\lesssim 45 \mu\text{s}$. The QPO investigated here have fractional rms amplitudes and widths comparable to those of the horizontal-branch oscillations in the Z sources but their frequencies are 10–40 times higher, so we are sensitive to time lags 10–40 times smaller. In 4U 1608–52, the $\sim 27 \mu\text{s}$ time lag is equivalent to a phase difference of ~ 0.13 radians, or about 8° .

The time lags we have measured can be used to derive general constraints on the X-ray production mechanisms in these systems (see Lamb 1988). It is important to consider these constraints in the larger context of the time lags, energy spectra, power spectra, and cross coherence between the oscillations at different photon energies. Any physical model should be consistent with all four of these statistical properties. If the X-ray spectrum is not formed predominantly by Compton scattering, then the ~ 800 Hz oscillation at 11–16 keV must be produced so that it lags the oscillation at 4–6 keV by $\sim 27 \mu\text{s}$ in 4U 1608–52. Delays must be $\lesssim 45 \mu\text{s}$ in 4U 0614+091 and 4U 1636–53. The high value ($\gtrsim 0.85$) of the cross coherence in 4U 1636–53 and 4U 1608–52 requires that if the source of photons responsible for the QPO is physically extended, the lags in the emission process must be independent of location (Vaughan & Nowak 1997; Nowak & Vaughan 1996). Any model in which the QPO are produced at the surface of a neutron star that is also a pulsar must explain why the QPO are seen but the periodic oscillations are hidden.

We now consider models in which photons produced near the neutron star are upscattered by electrons in a region with optical depth $\tau \gtrsim 1$. Optically thin free-free emission in a scattering region $\lesssim 100$ km in size supplies too few photons to account for the observed luminosity of the atoll sources, which is $\sim 0.1 L_{\text{Edd}}$. Hence, the photons must be produced in a self-absorbed region, such as the outer layers of the neutron star. Given the observed luminosities of these sources, any thermal emission from the neutron star peaks at ~ 1 –2 keV. No such peak is observed, indicating that the scattering region has an optical depth of $\gtrsim 3$. Models of this type provide a natural explanation for the X-ray spectra of these sources (see Lamb 1989; Psaltis, Lamb, & Miller 1995) and may also offer an explanation of their rapid x-ray variability (see Miller, Lamb, & Psaltis 1997 for an overview). We analyze the generic properties of models of this type, avoiding special geometries or physical conditions.

The fractional rms amplitudes of the kilohertz QPO can be used to place an upper bound on the sizes of emitting regions in all kilohertz QPO sources. Quite generally, the size of the region must be less than a few times c/ν_{QPO} , independent of the QPO mechanism, since radiation from different parts of the region have different path lengths to the observer, causing phase shifts that attenuate the QPO signal. If the radiation is scattered, the rms amplitude at infinity of a luminosity oscillation with frequency ν and amplitude A_0 at the center of a spherical region of radius a and optical depth τ is $A_\infty \simeq (2^{3/2}xe^{-x} + e^{-\tau})A_0$, where $x \equiv (3\pi\nu a\tau/c)^{1/2}$ (Kylafis & Phinney 1989). The ~ 800 Hz QPO studied here have rms amplitudes $\sim 10\%$,

so if they are luminosity oscillations the scattering region must be smaller than ~ 200 km if $\tau \sim 5$. If instead they are beaming oscillations, the scattering region must be smaller than ~ 100 km if $\tau \sim 5$. These bounds are almost independent of the electron temperature and bulk velocity in the scattering region, and remain approximately valid for non-spherical regions.

The time lags reported here, if caused by upscattering, provide stringent constraints on the size, a , of the upscattering region. We first compute a rough, qualitative estimate of a . If photons with energy E_{in} are injected into a scattering region where the electron temperature T_e is $\gg E_{\text{in}}/k_B$, they will gain energy each time they scatter, so photons that escape with a higher energy E_2 emerge later than photons that escape with a lower energy E_1 . The delay δt in the arrival time at a distant observer of photons of energy E_2 relative to photons of energy E_1 depends on the geometry of the region and the spatial distribution of its electron density and temperature but will be $\sim \Delta u \ell / c$, where ℓ is the photon mean free path and Δu is the difference in the average number of scatterings experienced by photons that emerge with energies E_1 and E_2 . If $\Delta u \sim u$, where u is the average number of scatterings to escape from the cloud, then $\delta t \sim au/c\tau$, where $\tau = a/\ell$ is the optical depth. For $\delta t \sim 27 \mu\text{s}$, $\tau \sim 5$, and $u \sim \tau^2$, the inferred size of the scattering region is a few kilometers.

To estimate the size of the region more quantitatively, note that if the scattering electrons are nonrelativistic, then after one scattering the average energy of a photon with initial energy E_{in} is $E \sim E_{\text{in}} \exp(4kT_e/m_e c^2)$, where m_e is the electron rest mass (see Rybicki & Lightman 1979, Ch. 7). Therefore, the ratio of the energies of two photons that experience a different number of scatterings is $E_2/E_1 \sim \exp(4\Delta u kT_e/m_e c^2)$. Solving this expression for Δu and using the above expression for δt gives (see, e.g., Sunyaev & Titarchuk 1980)

$$\delta t \sim \frac{a}{c\tau} \frac{m_e c^2}{4kT_e} \ln \left(\frac{E_2}{E_1} \right). \quad (1)$$

For 4U 1608–52, we have measured $c\delta t$ to be ~ 8 km for $E_1 = 5$ keV and $E_2 = 14$ keV, and hence $a \sim 8\tau(4kT_e/m_e c^2)$ km.

Photons injected with energies $E_{\text{in}} \ll kT_e$ into a region with a Compton parameter $y \equiv 4kT_e\tau^2/(m_e c^2)$ that is less than the saturation value $y_{\text{sat}} \sim 10$ emerge with a spectrum that is roughly a power law with an exponential cutoff at $\sim 2kT_e$. The countrate spectra of the atoll sources indicate $kT_e \gtrsim 10$ keV (White, Stella, & Parmar 1988), in which case a must be greater than $\sim \tau \cdot 1$ km. Compton upscattering produces hard time lags only if it is unsaturated, i.e., only if $y \lesssim y_{\text{sat}}$, so a must also be less than $\sim 8(y_{\text{sat}}/\tau)$ km. Combining these upper and lower limits, we find

$$5 \left(\frac{\tau}{5} \right) \text{ km} \lesssim a \lesssim 16 \left(\frac{y_{\text{sat}}}{10} \right) \left(\frac{5}{\tau} \right) \text{ km}, \quad (2)$$

where we have scaled the expressions to $\tau \sim 5$, the value suggested by models of the X-ray spectra and rapid X-ray variability of the atoll sources (see for example Lamb 1989; Psaltis, Lamb, & Miller 1995).

In this analysis we have assumed that soft photons are injected at the center of a spherical region of uniform temperature and electron density. If any of these conditions are not satisfied, the bounds on the size of the Compton upscattering region are larger than those derived above. We have also assumed that $E_2 \ll 2kT_e$. If instead $E_2 \sim 2kT_e$, the energy change in each scattering of photons with energy near E_2 is significantly less than we have assumed, so δt is significantly greater than in equation (1) and the bounds on a are correspondingly smaller than estimated above. However, the value of E_2 used here (14 keV) is less than the ~ 20 keV lower bound on $2kT_e$ inferred from the X-ray spectra of the atoll sources, so this effect is

probably small. We expect that the upscattering region is in reality inhomogeneous and that the size of the upscattering region is closer to the lower bound rather than the upper bound in inequality (2) (see Miller et al. 1997). This is natural since we know the 4U 1608–52 is a neutron star because it produces Type I X-ray bursts (see Brandt et al. 1992 and references therein).

Compton upscattering by electron orbital motions may also be important in forming the X-ray spectra of these sources. If the radiation field is nearly isotropic and the typical orbital velocity of the electrons is V , the spectrum that emerges from the scattering region is roughly a power law up to a cutoff energy $E_c \sim m_e c^2 (V/c)^2$ (Psaltis & Lamb 1997). For example, if $V/c \sim 0.15$, which can easily be attained in regions as close to the neutron star as we are considering, then $E_c \sim 10$ keV. If Compton upscattering by electron bulk motion is important, the time lags will depend upon the radial dependence of V , but the bounds on the size of the scattering region remain about the same.

In summary, the time lags we have measured indicate that the Compton upscattering region in 4U 1608–52 is between a few kilometers and a few tens of kilometers in size, i.e., comparable to the size of a neutron star.

The authors acknowledge Michael Nowak and Lev Titarchuk for useful comments and suggestions. BAV acknowledges support from the United States National Aeronautics and Space Administration (NASA) under grants NAG 5–3340 and NAG 5–3293. JvP acknowledges support from NASA under grant NAG 5–3271. FKL and DP acknowledge NSF grants AST 93–15133 and AST 96–18524 and NASA grant NAG 5–2925. MM is a fellow of the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78–277 and by the Netherlands Foundation for Research in Astronomy (ASTRON) under grant 781–76–017.

REFERENCES

- Alpar, A. & Shaham, J. 1985, *Nature*, 316, 239
- Berger, M., van der Klis, M., van Paradijs, J., Lewin, W. H. G., Lamb, F., Vaughan, B., Kuulkers, E., Augusteijn, T., Zhang, W., Marshall, F. E., Swank, J. H., Lapidus, I., Lochner, J. C. & Strohmayer, T. E. 1996, *ApJ*, 469, L13
- Bradt, H. V., Rothschild, R. E. & Swank, J. H. 1993, *A&AS*, 97, 355
- Brandt, S., Castro-Tirado, A. J., Lund, N., Dremin, V., Lapshov, I., & Sunyaev, R. 1992, *A&A*, 262, L15.
- Bussard, R. W., Weisskopf, M. C., Elsner, R. F., Shibasaki, N. 1988, *ApJ*, 327, 284.
- Dieters, S., Vaughan, B. A., Kuulkers, E. & van der Klis, M. 1997, *AA*, in preparation
- Kylafis, N. & Phinney, E. S. 1989, in *Timing Neutron Stars*, eds. H. Ögelman and E. P. J. van den Heuvel, (Dordrecht:Kluwer), p. 731
- Lamb, F. K. 1989, in *Proc. 23rd ESLAB Symp. on X-ray Astronomy*, ed. N. E. White (ESA SP-296), 215
- Lamb, F. K. 1988, *Adv. Space Res.*, 8, 421
- Lamb, F. K., Shibasaki, N., Alpar, M. A., Shaham, J. 1985, *Nature*, 317, 681
- Méndez, M., van der Klis, M., van Paradijs, J., Lewin, W. H. G., Lamb, F. K., Vaughan, B. A. & Kuulkers, E. 1997, *ApJL*, in preparation

- Miller, C., Lamb, F. K. & Psaltis, D. 1997, ApJ, submitted
- Mitsuda, K., & Dotani, T. 1989, PASJ, 41, 557
- Morgan, E. H., Smith, D. A. 1996, IAU Circ., 6437
- Nowak, M. A. & Vaughan, B.A. 1996, MNRAS, 280, 227
- Psaltis, D. & Lamb, F. K. 1997, ApJ, submitted
- Psaltis, D., Lamb, F. K., & Miller, G. S. 1995, ApJ, 454, L137
- Rybicki, G. B. & Lightman, A. P. 1979, “Radiative Processes in Astrophysics” (New York:Wiley)
- Stollman, G. M., van Paradijs, J., Hasinger, G., Lewin, W. H. G., van der Klis, M. 1987, MNRAS, 227, 7
- Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A., Titarchuk, L., Day, C. 1996, ApJ, 469, L9
- Strohmayer, T., Lee, U., Jahoda, K. 1996, IAU Circ., 6484
- Sunyaev, R. A. & Titarchuk, L. G. 1980, AA, 86, 121
- van der Klis, M., Hasinger, G., Stella, L., Langmeier, A., van Paradijs, J., and Lewin, W. H. G., 1987, ApJL, 319, L13
- van der Klis, M., Wijnands, R., Chen, W., Lamb, F. K., Psaltis, Kuulkers, E., D., Lewin, W. H. G., Vaughan, B., van Paradijs, J., Dieters, S., Horne, K. 1996, IAU Circ., 6424
- Vaughan, B. A., van der Klis, M., Lewin, W. H. G., Wijers, R. A. M. J., van Paradijs, J., Dotani, T., Mitsuda, K 1994, ApJ, 421, 738
- Vaughan, B. A. & Nowak, M. A. 1997, ApJ, 474, L43
- Vaughan, B. A., van der Klis, M., Lewin, W. H. G., van Paradijs, J., Dotani, T. & Mitsuda, K 1997, submitted to ApJ
- White, N. E., Stella, L. & Parmar, A. N. 1988, ApJ, 324, 363
- Wijers, R. A. M. J., van Paradijs, J. & Lewin, W. H. G. 1987, MNRAS, 228, 17
- Wijnands, R. A. D., van der Klis, M., van Paradijs, J., Lewin, W. H. G., Lamb, F. K., Vaughan, B. A. & Kuulkers, E. 1997, ApJL, submitted